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An investigation of the Kutta condition by pressure measurements on an oscillating hydrofoil for a range of reduced frequencies.

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AN INVESTIGATION OF THE KUTTA CONDITION BY
PRESSURE MEASUREMENTS ON AN OSCILLATING HYDROFOIL
FOR A RANGE OF REDUCED FREQUENCIES

by

RUSSELL HENRY BURT

B. S. United States Naval Academy
(1956)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
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I also wish to acknowledge the assistance received from numerous persons in connection with obtaining or fabricating equipment, especially Mr. Oscar Wallin of the Aeroelastic and Structures Research Laboratory Model Shop.

AN INVESTIGATION OF THE KUTTA CONDITION BY

PRESSURE MEASUREMENTS ON AN OSCILLATING HYDROFOIL

FOR A RANGE OF REDUCED FREQUENCIES

by

Lt. Russell Henry Burt, U.S.N.

Submitted to the Department of Naval Architecture and Marine Engineering on 22 May 1964, in partial fulfillment of the requirements for the Master of Science Degree and the professional degree, Naval Engineer.

ABSTRACT

This thesis attempts to determine if the assumption that the flow off the trailing edge of an oscillating hydrofoil section is smooth as it is in the steady state hypothesis of Kutta. Pressure measurements were made at several locations on a 19" span, 5" chord NACA 0010-34 hydrofoil. The measurements were made for one speed, one pitch angle and for a frequency range of 3 to 7 cycles per second.

The results are inconclusive as calibration errors, signal to noise level and general data scatter proved that the instrumentation employed was not sensitive enough. However, the measured pressures show the effect of added mass as the frequency is increased and indicate that the flow near the trailing edge may become separated.

Thesis Supervisor: Holt Ashley

Title: Professor of Aeronautics and Astronautics

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NOTATION

a_n	a complex constant
C	chord
f	frequency
k	reduced frequency $= \omega c/2V$
p	pressure
$\Delta \bar{p}$	magnitude of simple harmonic pressure fluctuations
m	constant of spanwise series
n	constant of chordwise series
S	span
$\bar{S}$	$= Y/S$ non dimensional spanwise coordinate
V	forward velocity
$\bar{v}$	magnitude of simple harmonic velocity
x	chordwise coordinate $x = \cos\theta$
z	vector position on mapped circle
θ	angle of z with axis
ψ	acceleration potential
ϕ	velocity potential
$\bar{\omega}$	complex potential
ω	circular frequency
$\lvert \bar{C}_p \rvert$	magnitude of simple harmonic non-dimensional pressure coefficient
ρ	density

I OBJECT

The object of this thesis is to measure the pressure for various reduced frequencies and pitching amplitudes at a grid of points and to compare the results with theoretical predictions based on the assumption that the Kutta condition is valid. The difference between the theoretical pressure and the measured pressure is an indication of the amount by which the Kutta condition is violated for the given motion. The theoretical pressure can then be modified by the insertion of a term with a singularity at the trailing edge. The resultant series can then be adjusted by trial and error variations in the strength of the singularity until agreement is reached.

This thesis is motivated by the many references in hydrofoil and airfoil literature attributing discrepancies to failure of the Kutta condition. Bisplinghoff, Ashley and Halfman (1) refer to this in several places, Parkin (2) uses it for a stationary foil, and Ransleben and Abramson (3) attributes a fall off in lift on an oscillating foil at high reduced frequencies to this discrepancy.

Ashley, Widnall, and Landahl (4) discuss the failure of the Kutta hypothesis at high reduced frequencies. They point out that previous force and moment measurements were made by varying the velocity at a fixed frequency and imply that the changing Reynolds number may have an important effect. Therefore all tests in this series will be run at a constant Reynolds number.

II THEORY

From two dimensional incompressible flow the complex potential for an oscillating cylinder (5) is

$$\bar{\omega} = \left(-a_o \frac{Z}{1+Z} + \sum_{n=1} \frac{a_n}{Z^n} \right) \qquad (1)$$

as $Z = e^{i\theta'}$ with θ' measured from the down stream singularity

$$\frac{Z}{Z+1} = \frac{e^{i\theta'}}{e^{i\theta'}+1} = \frac{1}{2} \frac{\cos\frac{\theta'}{2} + i \sin\frac{\theta'}{2}}{\cos\frac{\theta'}{2}}$$

The imaginary part of $\bar{\omega}$ gives the acceleration potential

$$\Psi = -\frac{a_o}{2} \tan\frac{1}{2}\theta' - \sum_{n=1} a_n \sin n\theta' \qquad (2)$$

Converting θ' to the angle measured from the leading edge $\theta = \pi - \theta'$

$$\Psi = +\frac{a_o}{2} \cot\frac{\theta}{2} + \sum a_n \sin n\theta \qquad (2a)$$

where the change in signs is taken up by the constants.

In linearized unsteady flow the perturbation pressure (6)

$$p - p_\infty = \Delta p = \Psi = \frac{\partial \phi}{\partial t} + \frac{\partial \phi}{\partial x} \qquad (3)$$

Watkins' representation for the pressure on a finite aspect ratio undergoing simple harmonic motion is

$$\frac{\Delta \bar{p}(\theta,s)}{4\pi\rho_\infty U^2} = \sqrt{1-\bar{s}^2} \left\{ \sum_{m=0} a_{om}\, \bar{s}^m \cot\frac{\theta}{2} + \sum_{m=0} \sum_{n=1} \frac{4}{2^{2n}} a_{nm}\, \bar{s}^m \sin n\theta \right\} \qquad (4)$$

where $\sqrt{1-\bar{s}^2}$ represents eliptical spanwise pressure distribution and $\Delta\bar{p}(\theta,s)\, e^{i\ \ t} = \Delta p(\theta,s,t)$.

The integral equation relating the normal velocity to the pressure distribution (4) is

$$\bar{v}_n(x,\bar{s}) = \oint\int \frac{\Delta \bar{p}}{4\pi \rho_\infty U^2} K \, d\xi \, d\sigma \tag{5}$$

where K is the Kernel function (6) which represents the normal velocity at $(x,\bar{s})$ due to a unit delta function of pressure loading acting normal to the surface of the foil in subsonic irrotational flow (4).

A boundary condition is that at the surface of the foil the normal velocity of the foil and the fluid must be the same. The downwash equation (5) can be solved for the pressure distribution (4) using the known motion of the foil to satisfy the right hand side of the equation and the known Kernal function (6).

III PRESENTATION OF RESULTS

The pressure was measured at seven of the sixteen points in the foil grid (Figure 3) while the foil was oscillating about the trailing edge at various frequencies and at a constant speed. Of these seven points the pressure records from four locations are suitable for analysis. The resultant pressures for points B2, C1, D1, and D2 are shown plotted in Figures 1 and 2. The recorded Sanborn amplitudes are shown in Figures 7 and 8.

The original step pressure method of calibration as described in Appendix D was used to convert the Sanborn deflections to pressure for point D1.

Discrepancies in the calibration procedure became apparent when analyzing the data from points B2 and D2. Since the equipment could not be recalibrated under the came conditions as the data was taken, the results of Laidlaw (7) were used to extrapolate a calibration factor for the lowest frequency at which the pressure was measured. This calibration factor was used to convert the measured amplitude to the pressure plotted for these points in Figure 2.

For point C1 the calibration used is that described in the procedure. The calibration was checked between each frequency run. A plot of the calibration for the series of frequencies is shown in Figure 10. The pressure divided by the square of the circular frequency is shown plotted in Figure 2a.

As a result of the test procedure, zero speed pressure was also measured. It is plotted in Figure 11 as Sanborn amplitude and in Figure 12 as pressure with the same calibration factors as were used for the points during forward motion.

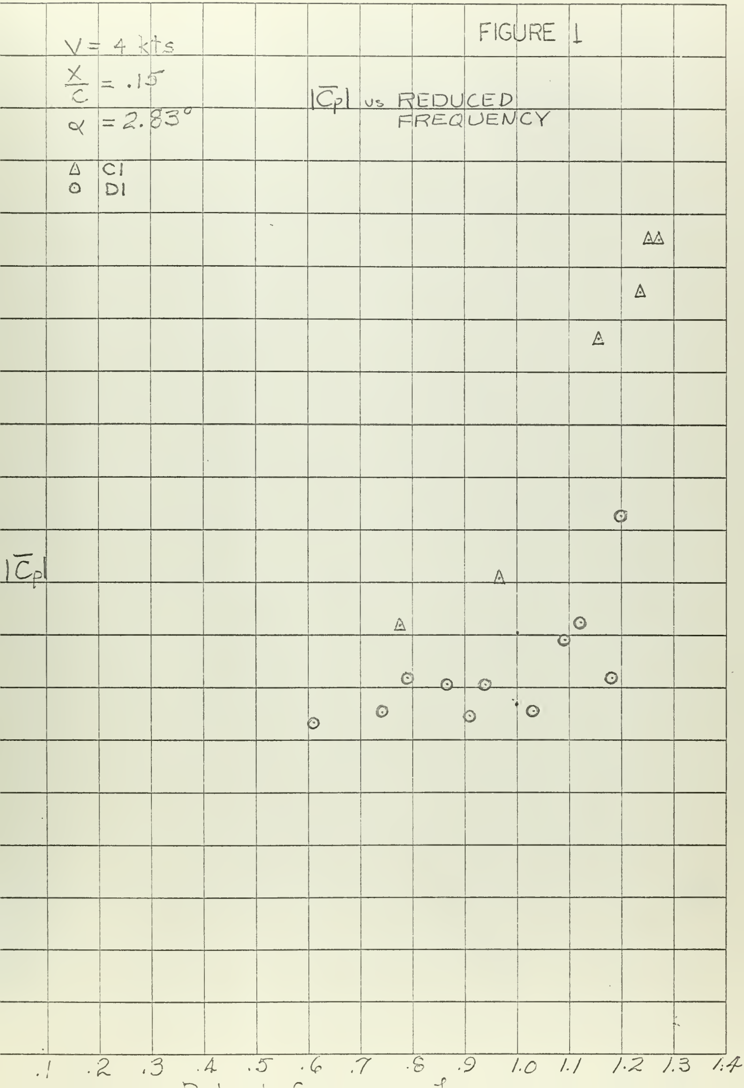


FIGURE 1
V = 4 kts
$\frac{X}{C} = .15$
$\alpha = 2.83°$
Δ C1
⊙ D1
$|\bar{C}_p|$ vs REDUCED FREQUENCY
$|\bar{C}_p|$
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4

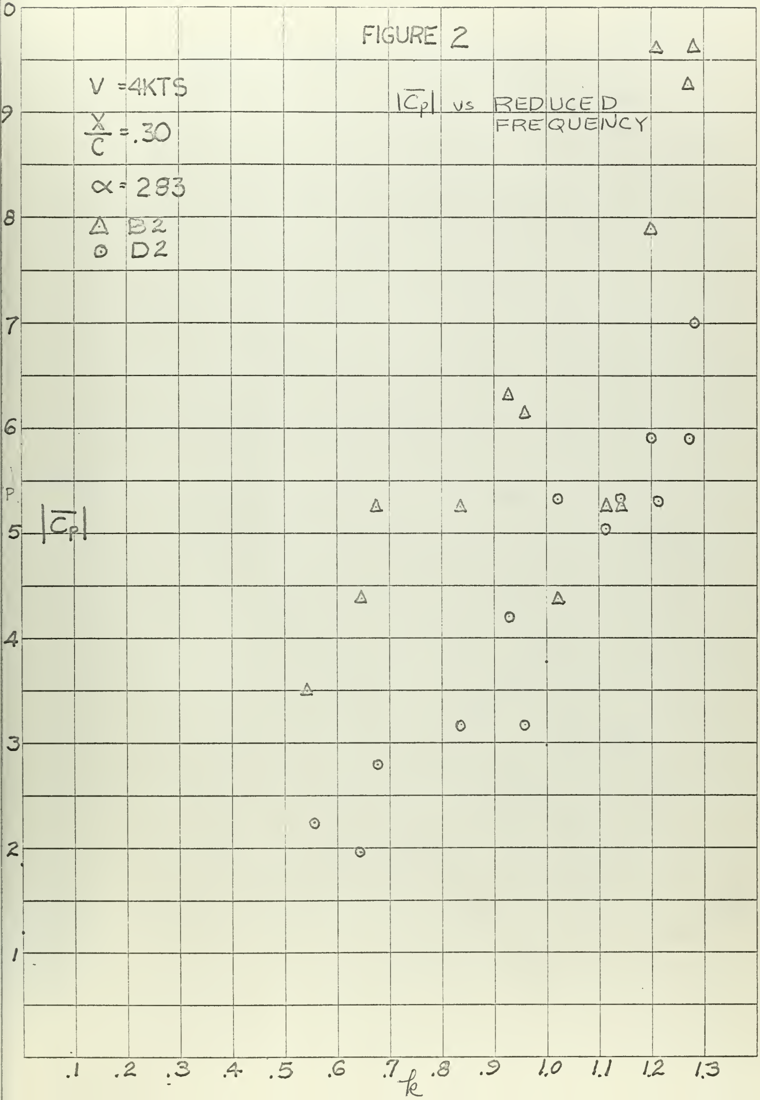
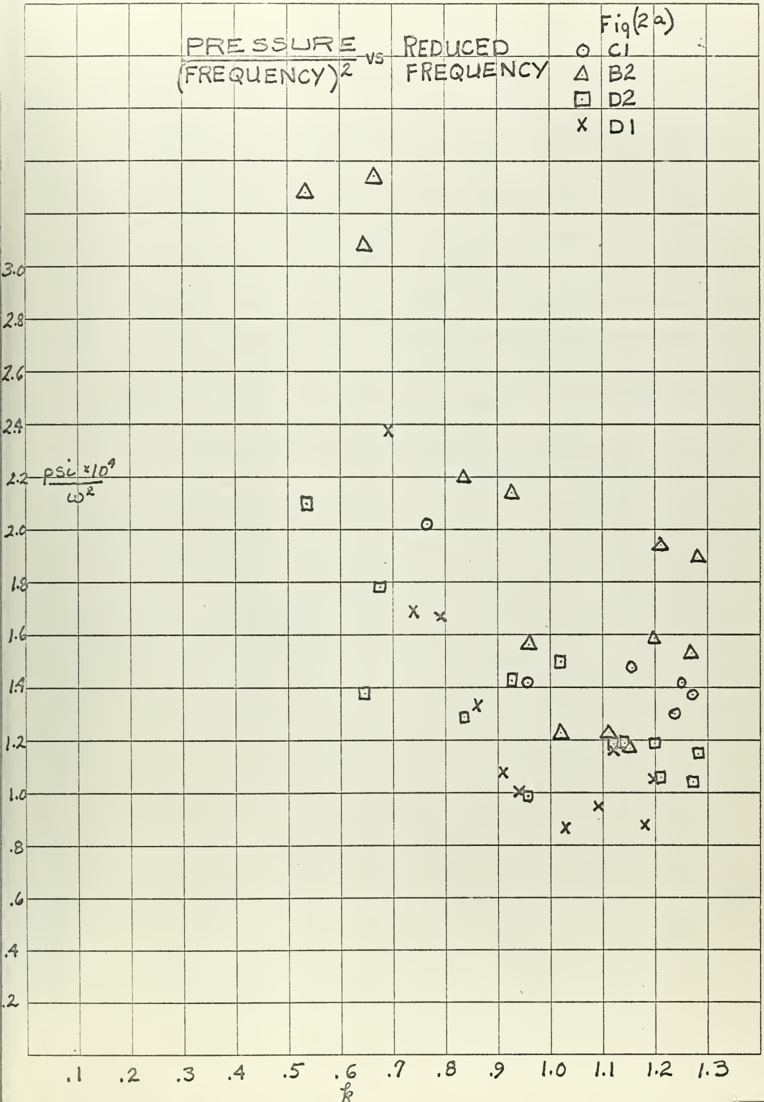


FIGURE 2
V = 4KTS
$\frac{X}{C}$ = .30
α = 283
Δ B2
⊙ D2
$|\overline{C_p}|$ vs REDUCED FREQUENCY
$|\overline{C_p}|$
k
0
9
8
7
6
5
4
3
2
1
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3



PRESSURE / (FREQUENCY)^2 vs REDUCED FREQUENCY
Fig (2a)
○ C1
△ B2
□ D2
X D1
psi ×10^4 / ω^2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3
k

IV DISCUSSION OF RESULTS

The results of this experiment indicate that the pressure at a point increases with increasing reduced frequency. The calibration problems encountered for all runs except C1 preclude accurate analysis of the data for these runs; however, the error may reasonably be assumed to be one of sensitivity for all data points at a given location. This means that the calibration is of the form $p = ea$ where e is a constant depending on location. The justification for e depending only on location comes from the calibration conducted between runs for point C1 which shows that the calibration remained constant throughout the run.

The only run from which definite conclusions as regard to pressure magnitude can be obtained is run C1. Here the effect of added mass becomes apparent as reduced frequency is increased.

The dependence of pressure on reduced frequency is not linear in the range $k = 0.5$ to $k = 0.8$ but appears to increase gradually. Above $k = 1.0$ the pressure is proportional to the square of the circular frequency or for this experiment the square of the reduced frequency.

V CONCLUSIONS

The object of this thesis was not accomplished. The experimental results were neither numerous enough nor accurate enough to draw specific conclusions regarding the Kutta condition. Calibration problems were sources of large error except for point C1. Another problem area was the signal to noise ratio. This was the reason that data taken from points B3 and D3 was not subject to analysis.

For the runs at points B3 and D3 (sample recording Figure 6a ~~25a~~) the signal to noise ratio was to large to detect the pressure component at the forcing frequency. This may be caused by intermittant separation of the fluid from the foil surface during part of the oscillating cycle.

VI RECOMMENDATIONS

The results included in this thesis are a small part of those necessary to draw firm conclusions. Therefore, the study should continue measuring the pressure distribution for other angles of oscillation, other axis of rotation and other speeds. The foil and oscillator described have provision for these tests. With the present type transducer D.C. amplifiers should be placed on the carriage to compensate for the line losses or a more sensitive pressure gage of the differential types should be obtained.

As in all experiments, the amount of data that could be recorded during one run was limited. It would have been advantageous to have installed a velocity meter in the foil near the free end. The output of this could be integrated to give the foil tip motion. If more data channels were available, the pressure at four points along the span could be measured at one time. This would eliminate the effect of spanwise motion errors.

The carriage of the MIT Ship Model Towing Tank is not stiff enough to run at high frequencies. Vibrations were set up in the carriage for runs with frequencies higher than 4.5. An effort is presently being made to stiffen the carriage.

APPENDIX A

Equipment

The foil is NACA 0010-34 (8) with a 5.0 inch chord and a maximum thickness of 0.5 inches. It is made of two $2\frac{1}{2}$ inch sections which have been machined from 2024S aluminum. The two sections are attached to a 3/4 x 1/4 steel spline. The after section is attached to the spline with five tapered pins and may easily be removed to facilitate movement of the pressure transducer within the foil. The foreward section is screwed to the spline and may also be removed. The after section contains a spanwise milled slot to carry the transducer leads.

Both sections of the foil have at the top a $\frac{1}{2}$" x $\frac{1}{2}$" section which attaches to a clamp on the end of the driving shaft. Both the clamp and the foil are drilled so that the foil may oscillate about the leading edge, the trailing edge, either quarter chord and mid-chord.

The driving shaft is 3/4" diameter steel stock. It is supported on a 6" channel steel frame with three pillow blocks. Midway between the bottom two pillow blocks an arm is keyed to the shaft. The arm links the shaft to the driving mechanism.

Power is supplied from a power driver motor which is controlled by a variac. The motor drives one gear of scotch-yoke type sine wave generator. The arm from the shaft is connected to the yoke by three followers arranged so that slack may be removed from this sliding, mating surface. Slack in the gear train may be taken out by adjusting the idler gear position.

The entire structure bolts onto the carriage of the MIT Ship Model Towing Tank. The towing tank is described by Abkowitz (9). It is interesting to note that the carriage presently runs suspended from the upper rail. The carriage drive motor which is shock mounted on a bed plate drives the carriage by friction on the rear rail.

Speeds are measured by counting the number of times in an interval that hole in a disk passes a fixed photo cell. The disk is driven by a string attached to the carriage and running the entire length of the tank.

APPENDIX B

1. Instrumentation

The pressure on the foil surface was measured by an Atlantic Research LD80 piezoelectric transducer. This transducer consists of a 1/16" piezoelectric crystal mounted in a stainless steel holder. The crystal is covered by a thin waterproof coating. The transducer mates with a Micro-Dot connecter. This connecter is not waterproof so it was covered liberally with General Electric RTV102 silicon waterproofing compound.

The transducer was mounted in the foil and submerged to a depth of about 24". This made a cable run of about 36" from the transducer to the electrometer. A low noise coaxial cable with low capacitance was used. The electrometer described by Ruetenik (10) and Eagleson and Perkins (11) has the required impedance.

The output from the electrometer was fed to a Sanborn 150-1500 low level preamp and recorded on moving paper for later analysis.

2. Transducer Selection

The limitations placed on the pressure transducer by this experiment made the selection of a transducer quite difficult. The static pressure at the various grid positions ranged from 0.435 to 0.786 psi and the pressures that it is desired to measure require a gage that is sensitive to 0.001 psi in order to measure the pressure near the trailing edge. This implies that a differential pressure transducer should be employed. This would solve several problems by giving the desired $p_{upper} - p_{lower}$ at one location in addition to removing the static head. Most commercial differential pressure transducers however require a dry gas as the reference media. These may be employed by pressurizing the reference side with a dry gas to the level of the static pressure and then measuring the pressure on

one side of the foil at a time.

Another limitation on the transducer is size. In order to obtain a foil of reasonable dimension for use in the MIT Towing Tank and one which could be made in two sections on the available automatic milling machine a 5 inch chord was selected (2 - $2\frac{1}{2}$ sections). For the NACA 0010-34 profile the maximum thickness is 0.5" thus the maximum thickness of the pressure transducer cannot excede 3/8".

A third limitation on the transducer is frequency response. The frequency range of interest is from 3 to 7 cycles per second. This limitation is apparent when using piezoelectric transducers.

A fourth restriction on the transducer is the acceleration sensitivity. The transducer must be installed close to the point of measurement to obtain dynamic response therefore is subject to the oscillitory motion.

No transducer meeting all of these requirements was available. The first transducer used was a Kulite-Bytrex HFD2. This transducer is a differential pressure gage with a diaphram supported in the center by a semiconductor strain gage. The main advantage of this transducer is the small size (1/8"D x 1/8") which facilitated placement in the foil. The major disadvantage was low sensitivity. As the reference side of the transducer had been sealed at atmospheric pressure, the diaphram developed a set under the hydrostatic load reducing the sensitivity. The small size also made moving the transducer without damage from one location to another quite difficult.

The second transducer used was the Atlantic Research LD80 peizo-electric type. The main advantage of this transducer was its availability. Two transducers were obtained on loan from the U.S. Navy Underwater Sound Laboratory. The disadvantages which were known prior to its use included

frequency response, low sensitivity and the non-water-tightness of the connecter. The last of these caused failure of the equipment as the crystal resistance was decreased raising the low frequency cut-off point above the region of interest.

3. Cables

The cable connecting the output of the D.C. filter to the recorder is part of the Towing Tank installation and is of necessity at least as long as the Towing Tank. With the low signal levels this length became a factor in system sensitivity.

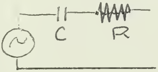
4. Amplifier-Recorder

Due to the low signal levels of the transducer, the Sanborn low level preamplifiers 150-1500∅ were used. These preamplifiers give 1 cm deflection for 100 V and are linear to 15 cps. They were obtained from the gyro shop of the Instrumentation Laboratory.

APPENDIX C

Piezoelectric Transducer

The Atlantic Reserach LD80 piezoelectric transducer contains a 1/16 inch diameter PZT5 crystal. The piezoelectric transducer produces a voltage when it is mechanically strained which is proportional to the straining force. The mechanical and electrical characteristics of the transducer depend on the shape and the size of the crystal. As the straining force is the change in pressure, the sensitivity of a ceramic crystal is reduced as frequency of pressure fluctuations is reduced. The frequency at which the loss of sensitivity becomes important is the product of capacitance of the crystal (C) and the impedance of the amplifier to which it is connected. As such the crystal and amplifier behave as a high pass filter



with a time constant of

$$\tau = RC$$

This gives a frequency response cut off of

$$\frac{1}{\tau} = \omega$$

In order to make ω become 3 cycles/second the product RC must be 0.53. The capacitance given by the manufacturer for the transducer is 40 $\mu\mu$farads. This requires an input impedance of the amplifier of 1.325×10^{10} or larger. The response of the system to a step change in pressure can be used to measure the actual time constant by measuring the time required for the output signal to decay to 1/e of its peak value in response to instantaneous change of pressure.

The measured time constants for both transducers and associated leads and amplifiers indicated a frequency response cutoff of the system to be 3 cps when the transducers were mated to the test pressure chamber. Measuring the low frequency cutoff by using a constant amplitude various frequency method such as is described in the procedure yielded a low frequency cutoff of 2.25 cycles/second.

Reference (12) covers the theory of dynamic pressure transducer calibration and shows the limitations of step calibration. Reference (13) discusses the effect of the time required to execute a pressure change.

APPENDIX D

Transducer-System Calibration

Several methods of calibration were attempted. The first of these was to use the response to a step change in pressure. The transducers were connected by a short length of flexible tubing to a cylindrical pressure chamber which was filled with water except for a small air pocket at the top. This air pocket had one outlet connected to a quick-opening solenoid valve and another to a manometer and to a hand bulb. The procedure followed is described by Eagleson, et al (13) and by reference (12). This procedure was not satisfactory as it could not be carried out with the transducers in the foil and the electronics on the carriage.

The calibration results or the system sensitivity were changed by the various ground potentials in the system. Placing the foil and electronics on the carriage introduced a different ground potential. Grounds were also changed by various methods while removing 60 cycle A-C noise.

A second method of calibration, which was unsuccessful, was to generate waves and measure the wave height over the foil while simultaneously recording the transducer output. The installed wave height measuring system and the wave generating system both proved inadequate for the desired frequency. As wave pressure decays exponentially with depth and frequency squared, this procedure would require moving the foil for calibration. Therefore no calibrations were made this way.

The final method of calibration is described in the procedure section and proved satisfactory although quite inconvenient. This type calibration was made between the various frequency runs with the transducer in position C1. It did not change with time or frequency indicating that two calibrations with the equipment in one location are all that are required, one prior to making the runs and one after completing them.

APPENDIX E

Procedure

The transducers were connected to their associated electronics and cables and then calibrated with the pressure vessel to get the step response for various changes in pressure and to determine the circuit time constants. The sensitivity control of the Sanborn Recorders was then adjusted so that both channels have the same amplitude response for various frequencies. The foil was then assembled with the transducer in a preselected location and placed in the water.

The chamber leading to the pressure transducer was filled with water and flushed by keeping two entrance ports open until the foil was under water. A hypodermic needle filled with water forced fluid through the chamber. The second part was closed after the chamber was flushed.

It was again calibrated by oscillating the foil up and down in its own plane. This was done by attaching the foil with a special shaft to the tie bar of the scotch yoke oscillator which had been removed from the assembly frame and placed on the towing tank work platform. This procedure produced dynamic calibration points for one change in pressure and at several frequencies with the transducers in the foil.

The calibrated foil was attached to the driving shaft and set for zero angle of attack. The driving mechanism was then replaced. By adjustment of the motor voltage with the variac a desired frequency could be obtained.

The carriage with the oscillating foil was then moved to the far end of the towing tank for the start of a run because a more constant speed is obtained in running toward the control station.

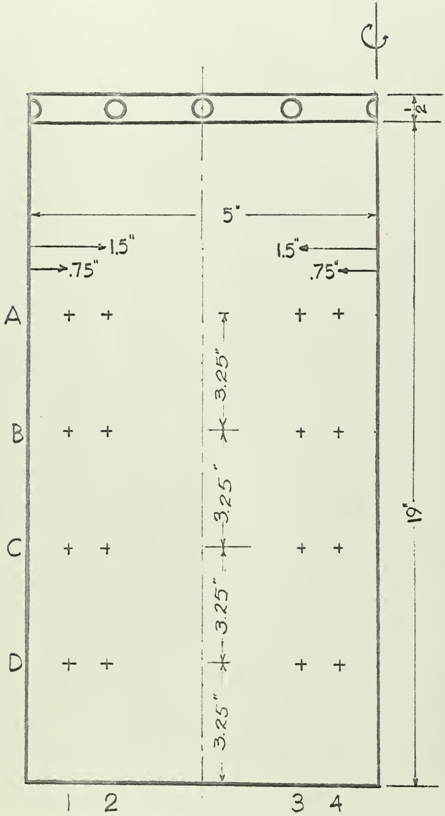
All runs were made at one speed (4 kts) so that Reynolds Number remained

constant. The speed indicator was calibrated with an oscillator to give 10 mm per knot. A motor voltage of 200^{V} gave 4 knots speed. The speed was also displayed on an events counter.

As the foil has been calibrated with the transducer in place several runs could be made at various frequencies prior to repeating calibration.

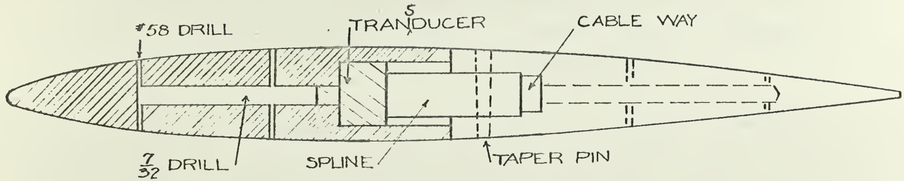
APPENDIX F

FIGURES



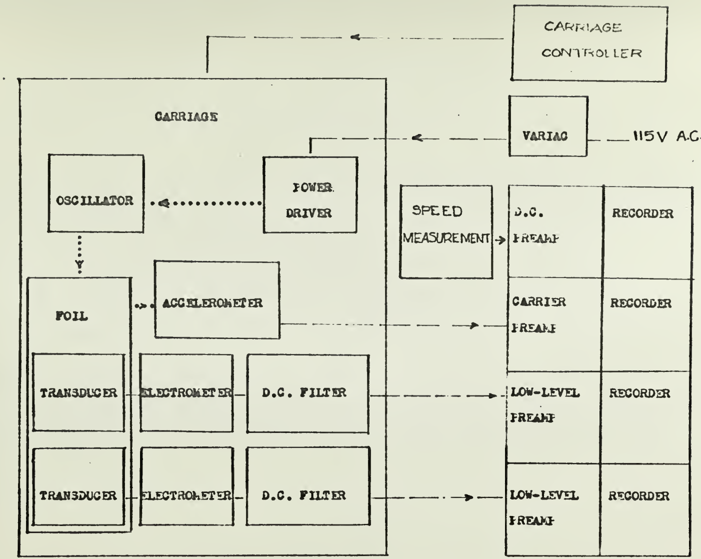
FOIL GRID

FIG 3



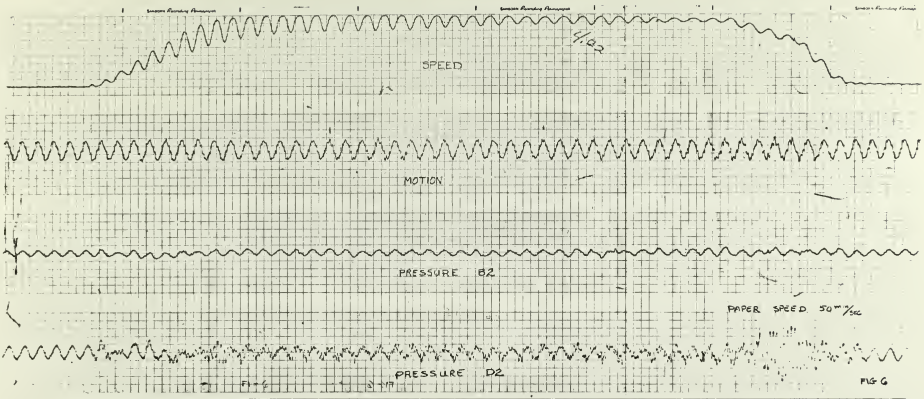
FOIL SECTION
NACA 0010-34

FIG. ~~3A~~ 4



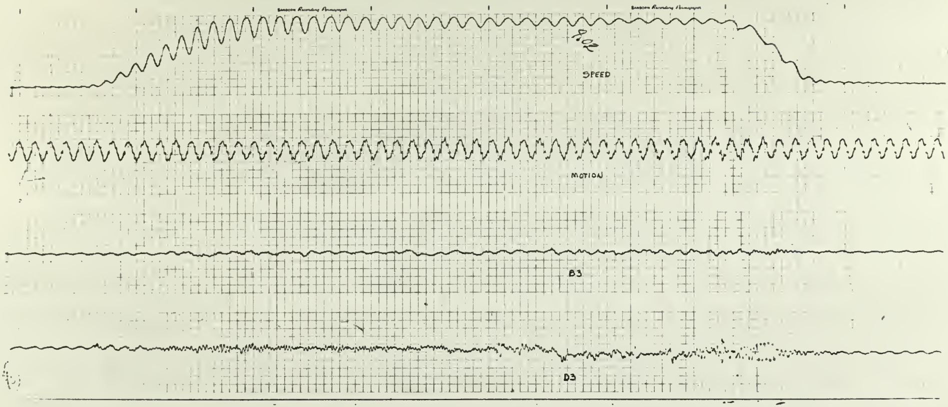
FLOW DIAGRAM

FIG 5



SAMPLE RECORDING

FIG 6



SAMPLE RECORDING

FIG 6A

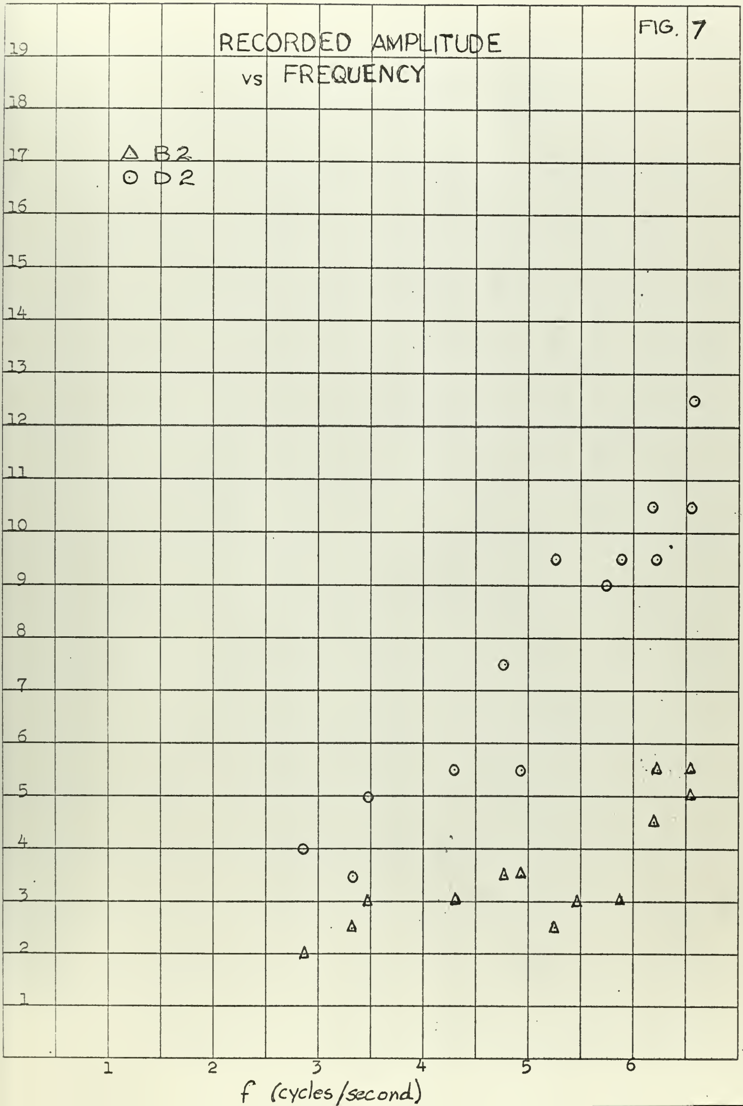


FIG. 7
RECORDED AMPLITUDE
vs FREQUENCY
△ B2
⊙ D2
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
f (cycles/second)

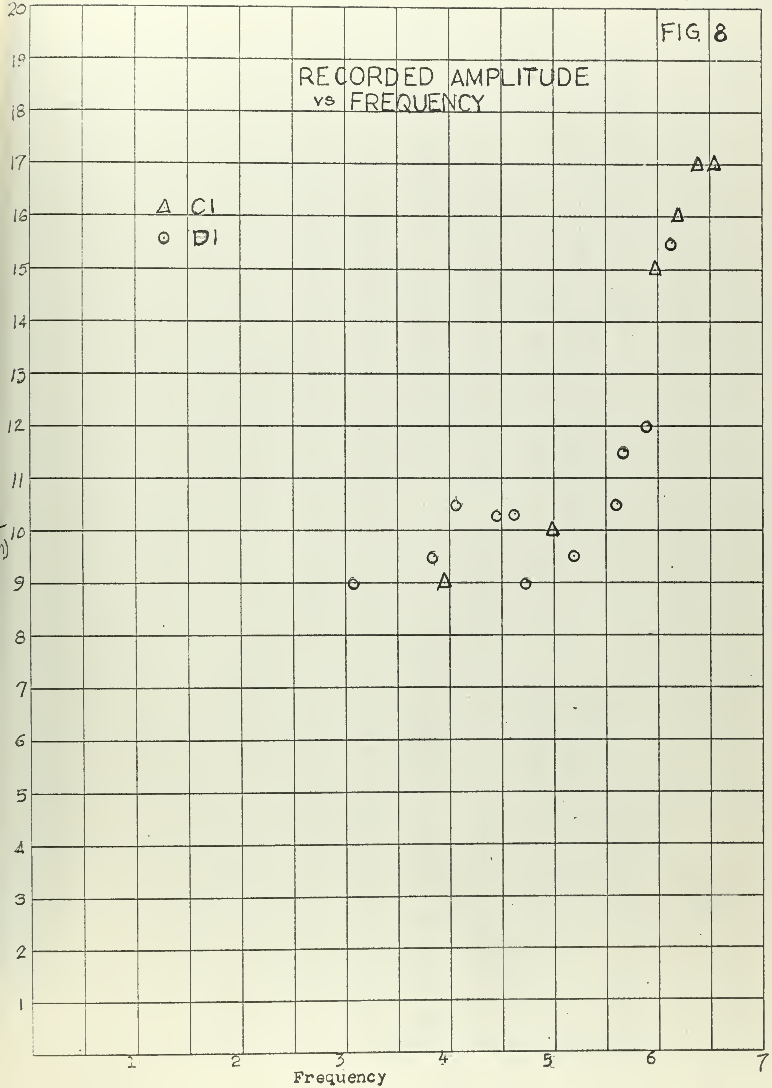
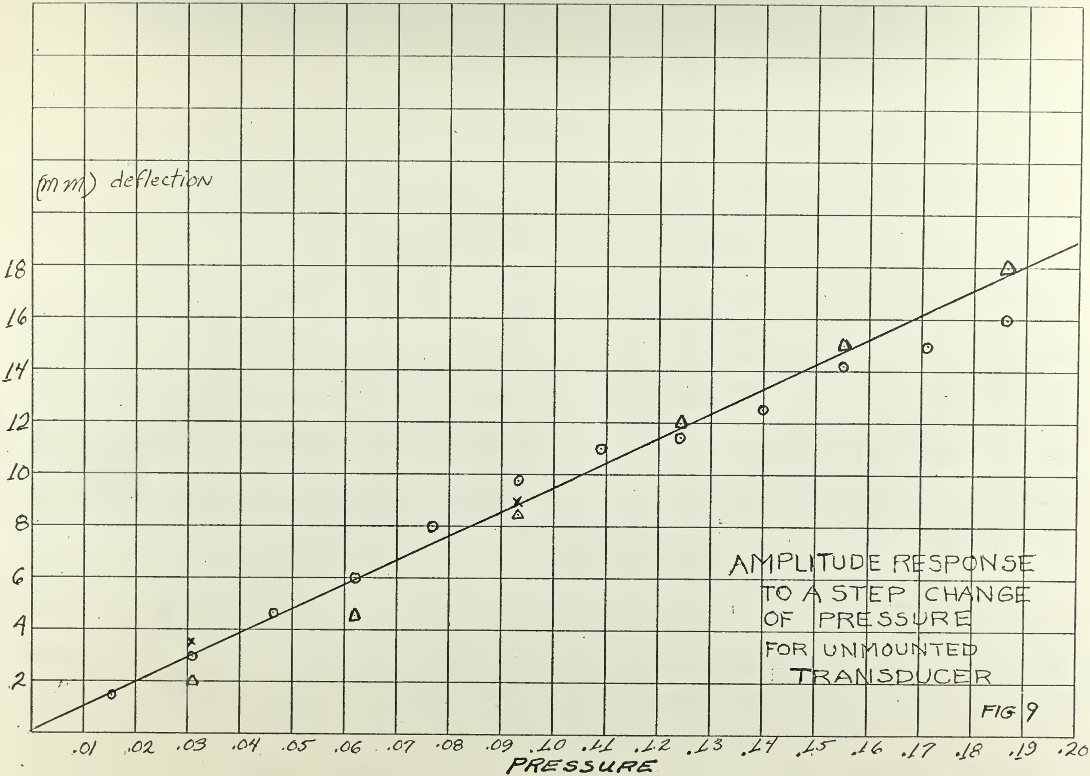


FIG. 8
RECORDED AMPLITUDE
vs FREQUENCY
Δ C1
⊙ D1
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
Frequency


(mm) deflection
18
16
14
12
10
8
6
4
2
.01 .02 .03 .04 .05 .06 .07 .08 .09 .10 .11 .12 .13 .14 .15 .16 .17 .18 .19 .20
PRESSURE
AMPLITUDE RESPONSE
TO A STEP CHANGE
OF PRESSURE
FOR UNMOUNTED
TRANSDUCER
FIG 9

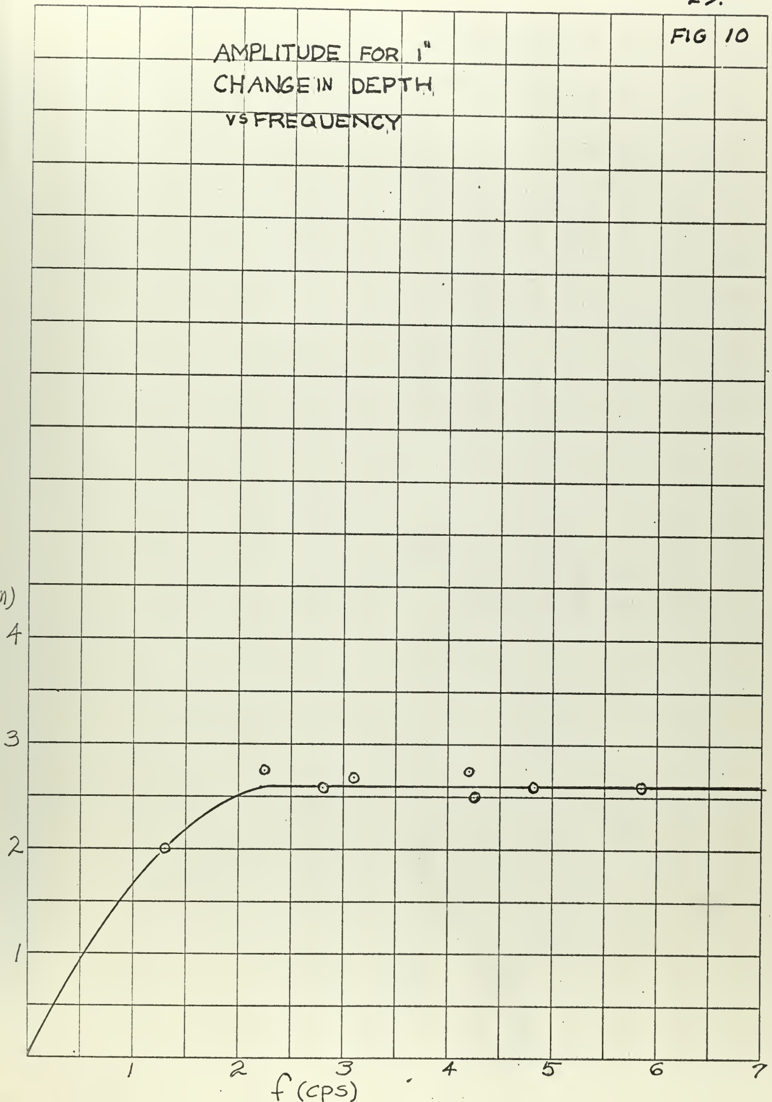
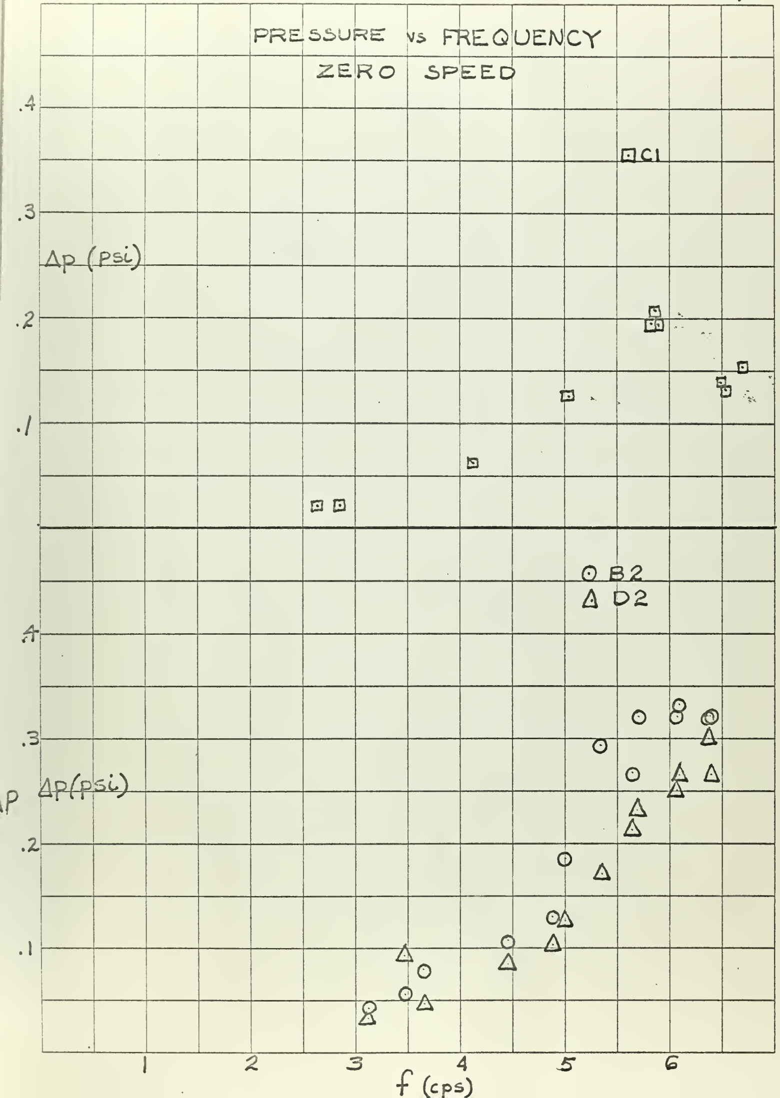
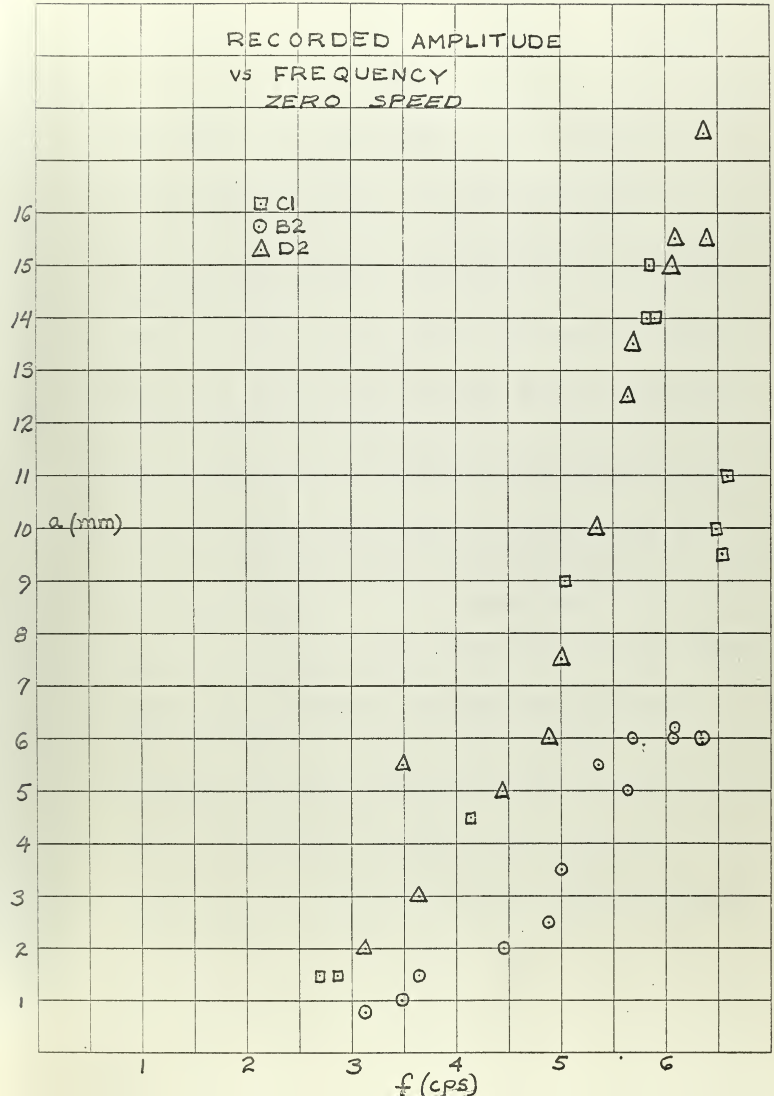


FIG 10
AMPLITUDE FOR 1"
CHANGE IN DEPTH
VS FREQUENCY
4
3
2
1
1
2
3
4
5
6
7
f (CPS)


PRESSURE vs FREQUENCY
ZERO SPEED
C1
Δp (psi)
.1
.2
.3
.4
B2
D2
Δp(psi)
1
2
3
4
5
6
f (cps)


RECORDED AMPLITUDE
VS FREQUENCY
ZERO SPEED
C1
B2
D2
a (mm)
f (cps)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

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